

# **Human Growth, Environmental Stress, and the Costs of Reproduction.**

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Height has been shown to vary among human populations in relation to a variety of environmental factors, including climatic conditions, diet, socio-economic status, and disease (Rona and Chinn, 1991; Waterlow and Schürch, 1993; Bogin, 1999; Wadsworth et al., 2001; Bogin et al., 2002; Mascie-Taylor and Lasker, 2005). In the 1980's it was argued that the reduction in human height observed in developing countries is an adaptive response that allows humans to avoid functional impairment as the result of malnutrition (Seckler, 1980). Under this view, height reduction would be a no-cost adaptation to suboptimal environmental conditions and individuals would be “small but healthy” (Seckler, 1980). However, research in human biology has shown that severe reduction in height-for-age (stunting) is a major sign of poor health, and is associated with compromised immune competence, poor psychological performance, diminished productivity, reduced reproductive potential, and increased mortality risk (Martorell, 1989; Paajanen et al., 2010). Stunting may affect up to 60% of the population in developing countries (WHO, 2010) and is relatively widespread even among the poorest segments of the United States population (Lewit and Kerrebrock, 1997). Therefore, an improved understanding of the causes and mechanisms of variation in height is extremely important to health and nutrition policy.

## **Human Growth and Environmental Stress**

Since different segments of the human body grow at different rates during different phases of development (Humphrey, 1999; Nyati et al., 2006), the lower limb bones tend to reach adult

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size earlier than the trunk (Bass et al., 1999; Bradney et al., 2000). This difference in the timing and tempo of skeletal growth implies that disruptions during development can affect body proportions (Karlberg, 1989). Given that childhood is characterized by fast long bone growth, perturbations during this growth period typically have the greatest impact on long-term development and are expressed in relatively shorter lower limb length (Karlberg, 1989; Allen, 1994).

However, human growth is a relatively plastic process and a variety of factors can intervene and affect the final achieved stature and proportions. First, under improved conditions individuals previously exposed to stressors may fully recover (catch-up growth) from environmental perturbations (Martorell et al., 1994; Cameron et al., 2005). Second, it has been argued that the sexes may respond differently to environmental stressors. Even though evidence is not conclusive, females may be more buffered than males against growth disruptions (Stini 1969). Third, under stressful conditions growth may be delayed and continue beyond an individual's teen years (Roche and Davila, 1972; Riley et al., 1989). Therefore, it is possible that growth may be affected by the costs of reproduction, especially in females (Scholl et al., 1993; Scholl et al., 1994; Casanueva et al., 2006; Rah et al., 2008). As a consequence, the complexity of human growth, the unpredictability of its disruptions, and the plastic response of different genotypes to stressors hinder interpreting variation in skeletal growth.

### **Biocultural Approaches in Human Biology**

A way to improve the understanding of the causes and mechanisms of variation in height and body proportions is to complement growth data with biocultural information. Biocultural approaches in human biology recognize that culture is an intrinsic aspect of human nature and plays an integral role in shaping the environment in which growth and development take place

(Dufour, 2006). Consequently, recording and measuring both biological and cultural variables is essential for improving the understanding of the causes of biological variation.

To this end, height and body proportions were examined at the *intra-population* level among rural Amazonian adults in relation to a number of biocultural factors. Specifically, long-term, longitudinal fieldwork conducted in the region provide detailed biocultural data including demographic patterns, reproductive histories, and health, as well as ethnographic data on cultural practices critical for interpreting data on human growth patterns (Piperata and Dufour, 2007; Piperata, 2007; Piperata et al., in press).

### **Research Objectives and Hypotheses**

The goal of this study is to draw on this rich data set to address models of human growth and test the following research hypotheses:

1. *Males and females respond differently to environmental stressors.* Based on the hypothesis of greater male susceptibility to environmental insults, all other factors being equal, males are expected to show a greater negative response to stressors than females. Specifically, since it has been shown that the lower limb is more affected by negative environmental conditions than the trunk (Bogin et al 2002), males are expected to have relatively shorter lower limbs than females.
2. *Severe height reduction (stunting) is associated with changes in body proportions.* Assuming that the lower limb is the segment most affected by environmental perturbations, it is expected that stunting will be due primarily to relatively shorter legs than trunks (Bogin et al., 2002). This is expected to occur similarly in the sexes.
3. *Female skeletal growth in suboptimal conditions is negatively affected by the costs of reproduction.* Under conditions of environmental stress, skeletal growth can be prolonged

into the early 20's and can possibly overlap with reproduction (Riley et al., 1989). In these instances, it is expected that maternal growth will be negatively affected by the costs of reproduction and that significant associations between reproductive history parameters and growth will be found.

## **MATERIALS AND METHODS**

### **People and field site**

This study explored intra-group variation in height and proportions in a population of Brazilian *Ribeirinhos* living in upper-land (*terra firme*) communities located in and around the Caxiuanã National Forest in the State of Pará (Piperata, 2007) (Fig. 1). The communities are rural, had no electricity or running water, and only a few households had pit toilets. The majority of households used the forest and river for waste disposal. Water for cooking was collected from the river or, in a few cases, from hand-dug wells, and trash was burned, buried, or dumped in the river. Most households consisted of a nuclear family but some included extended kin. Average household size was 7.6.

All the people practiced slash and burn agriculture with bitter manioc (*Manihot esculenta* Crantz) as their staple crop. Manioc was consumed primarily in the form of *farinha*, a toasted meal, and was the most important source of calories and carbohydrates in the diet (Murrieta et al., 2008; Piperata et al., in press). Fish, and to a lesser extent hunted game, were the most important sources of protein, and *açaí* (*Euterpe oleracea*), a local palm fruit consumed primarily in the form of a juice, was an important seasonal source of calories (Piperata et al., in press). While the people cultivated, fished, hunted, and collected the majority of the food they consumed, they were also actively involved in and dependent upon the regional market economy. Men and women shared the work associated with the cultivation and processing of

manioc (Piperata, 2005). Fishing, hunting and the collection of *açaí* were primarily male activities, although women cleaned and prepared the fish and game and extracted the *açaí* juice. Women were also responsible for all housework and childcare.

Structured interviews were used to gather information on household size and composition and women's reproductive histories. Ethnographic data on daily life, work and dietary patterns and local beliefs regarding gender roles were collected through participant observation and with unstructured and semi-structured interviews with adult men and women.

### **Sample**

This study included a total of 172 (88 female; 84 male) adult individuals between 18-77 years of age. The sample is particularly well suited for addressing the research questions in that the population (1) is relatively genetically homogeneous, (2) does not exhibit a large degree of variation in economic status and (3) shared similar environmental stressors (under/malnutrition, infectious disease) during the period of growth and development.

### **Anthropometric and Biocultural Data**

Anthropometric data were collected between March and August of 2002 while the biocultural data were collected over a two-year period (2002-2004) (Piperata, 2007). All data collection methods were reviewed and approved by the Human Research Committee at the University of Colorado-Boulder (HRC no. 1001.2) and by similar committees in Brazil.

In order to assess intra-population variation in height and body proportions, height, sitting height and total leg length were examined in different population subsamples (male, female, stunted, non-stunted) (Table 1). Anthropometric measurements were taken following standardized procedures (Lohman et al., 1988) and recorded to the nearest 0.1 cm. Individual z-scores for height-for-age (HAZ) (Frisancho 2008) were used to assign individuals to different

growth-outcome groups, i.e. stunted and non-stunted. Stunting was defined as a low HAZ (z-score < -2) (WHO, 1995).

Structured interviews were used to gather detailed biocultural data on the individual participants including household size and composition. After the collection of the anthropometric data, a reproductive history was conducted with each of the 88 adult women and included information on age at menarche, age at birth of first child, parity and date of birth of each child. The birth dates of the individual children were used to calculate inter-birth intervals and their average.

### **Data Analysis**

Reduced Major Axis (RMA) regression and the “Quick-Test” devised by Tsutakawa and Hewett (1977) were employed to test the hypotheses that stunting would be associated with changes in body proportions and that males and females would respond differently to environmental stressors. Raw data were used in all analyses and age distributions across subsamples compared by Mann-Whitney or Kruskal-Wallis tests. Lastly, the association between linear growth (height, sitting height, and total leg length) and female reproductive history parameters (age at menarche, age at first birth, parity, and inter-birth interval between first and second birth) was explored using correlation analysis. Given the existence of a secular trend in age at first birth (see below), the obvious association between older age and parity, and the well-known phenomenon of age-related reduction in trunk height, all correlation analyses were controlled for age. Statistical analyses were performed using PASW Statistics 18.0, PAST (PAleontological Statistics) (Hammer et al, 2001), and Microsoft Excel 2007.

## **RESULTS**

### **Sex differences in response to environmental stressors**

Since there was no significant difference in age distributions of the male and female ( $p = 0.14$ ), sitting height over height was plotted for males and females and the joint distribution fitted by RMA regression (Fig. 2). The “Quick-Test” result was significant ( $p = 0.01$ ), indicating that the relationship between height and sitting height in the sample was significantly different between the sexes. Specifically, males tended to have relatively shorter trunks (sitting height) than females and thus, tended to cluster below the RMA line.

### **Changes in body proportions associated with stunting**

Males. Upon removal of the oldest individual in the population (77 years old), age distributions between stunted and non-stunted individuals in the population were tested using the Mann-Whitney test. No significant difference was detected, ( $p = 0.07$ ) therefore, sitting height over height was plotted for stunted and non-stunted males (Fig. 3). The results indicated no difference in the relationship between height and sitting between stunted and non-stunted males ( $p = 0.50$ ). In other words, stunting (or the process of stunting) appears to be isometric and not accompanied by detectable changes in sitting height/height proportions.

Females. The difference in the age distribution of stunted and non-stunted females in the population was non-significant ( $p = 0.09$ ). Figure 4 is the scatter plot of sitting height over height of stunted and non-stunted females in the population. The result of the “Quick-Test” was significant ( $p = 0.01$ ) meaning there was a significant difference in the relationship between height and sitting height in stunted and non-stunted females. In particular, stunted individuals tended to have relatively longer trunks than their non-stunted counterparts.

### **Relationship between skeletal growth and reproductive characteristics in females**

Reproductive characteristics for the women included in the study are reported in Table 2. A significant decline over time was detected in age at first birth (Fig. 5) with the trend of younger

women giving birth earlier than older women (Kruskall-Wallis test,  $p = 0.02$ ). Age at menarche did not differ among age groups ( $p = 0.66$ ) however, parity expectedly increased with age ( $p < 0.001$ ). Due to the relationship between reproductive life history variables and age, all correlation analyses (Table 3) were controlled for age. Age at first birth was the only reproductive history parameter that was significantly correlated with the anthropometric variables. Specifically, positive correlations were found between age at first birth and height ( $r = 0.29$ ;  $p = 0.01$ ), and age at first birth and total leg length ( $r = 0.41$ ;  $p = 0.001$ ).

## **DISCUSSION**

### **Sex differences in response to environmental stressors**

This study tested the hypothesis that males and females within the same population would respond differently to the same environmental stressors. Given the fact that the lower limb is more susceptible to environmental stress than the trunk (Bogin et al., 2002), all other factors being equal, males would be expected to exhibit relatively shorter legs than females. In contrast with expectations, males exhibited relatively shorter trunks (i.e. longer legs) than females. Several factors could be invoked to explain this finding, including differential treatment of children based on sex and the existence of sex-specific factors affecting growth.

Long-term ethnographic research in these communities revealed that, beyond the general division of labor based on sex, male and female children are treated equally in terms of access to food and medical care. However, adolescent boys were often served first at mealtimes and food was often set-aside for them if they were absent from the household when a meal was served. Even though this would not seemingly compromise other children's regular food intake, it is possible that adolescent males benefitted from improved nutrition and that this, in turn, allowed for catch-up growth and a relative increase in leg length during adolescence. Additionally, the



energetic stress of reproduction on females may also account for the observed sex differences in relative trunk/lower limb proportions in this population. Piperata and Dufour (2007) found that women in these communities had difficulty consuming sufficient calories to meet the energetic demands of milk production and were thus forced to draw on their own energy reserves.

Therefore, it is conceivable that women reproducing at a time when their own growth is not completed experience greater nutritional stress compared to adolescent males in the same population, explaining, at least in part, the differences in relative limb proportions observed.

Due to the existence of environmental stressors experienced by the sexes, the hypothesis of greater male susceptibility can find no support or refutation in this analysis.

### **Changes in body proportions associated with stunting**

This study also tested the hypothesis that stunting would be associated with changes in body proportions, with shorter individuals exhibiting relatively shorter legs. Contrary to expectations, there was no difference in body proportions between stunted and non-stunted males. This result would indicate that male height reduction in the population is rather isometric and that the stressors leading to stunting affected trunk and lower limb length equally. However, it should be noted that it is not possible to entirely rule out the presence of confounding factors such as age-related changes in trunk length and catch-up growth.

While differences in relative limb and trunk length were not found between stunted and non-stunted males, differences were found among the females. Specifically, stunted females tended to have relatively longer trunks (i.e. shorter legs) than their non-stunted counterparts. This result matches expectations and is consistent with what has been reported by other authors (Bogin et al., 2002). This result may be due, at least in part, to lack of catch-up growth, especially during adolescence, and/or increased nutritional stress associated with reproductive

costs during growth.

### **Female skeletal growth and the costs of reproduction**

Recent studies conducted among Mexican and Bangladeshi adolescents suggest that, in poorer settings, pregnancy during adolescence may lead to maternal growth cessation (Casanueva et al., 2006; Rah et al., 2008). However, it is important to note that both studies were conducted over a relatively brief period during the postpartum (1-6 months). Thus, it remains unclear if maternal growth resumed at some later point. Here, a different approach was adopted and the association between the final outcome of linear growth and reproductive history parameters such as age at menarche, age at first birth and parity was explored.

It has been argued that age at menarche, reflecting sexual maturation, may show an association with estrogen-induced epiphyseal closure and consequently with growth cessation (Porcu et al, 1994). No significant correlation was found between anthropometric variables and age at menarche. The positive correlation between age at first birth and total leg length suggests that early reproduction had a negative impact on the mother's own skeletal growth, particularly in relation to leg length. It seems reasonable to attribute the relative shortening of the lower limb observed to nutritional costs associated with pregnancy and lactation. It is interesting to note that, in this sample, growth retardation associated with early reproduction was limited to leg length, while sitting height was not affected. There is evidence indicating that the appendicular skeleton grows faster than the trunk during childhood, while the trunk growth velocity increases at the onset of puberty (Bass et al., 1999; Bradney et al., 2000). On this basis, one would expect stressors experienced later in growth – such as adolescent pregnancy and lactation – to have a greater impact on the axial rather than the appendicular skeleton. However, the findings of this study do not match expectations. The negative impact of reproduction on leg length may be due

to the fact that adolescent mothers in the developing world are farther from having reached adult leg length. Additionally, sitting height may be more constrained in size in relation to the size of the vital organs located in the chest and abdomen. Given the increased spatial demand in the torso associated with pregnancy, it seems reasonable to assume that leg length may be preferentially sacrificed.

## **CONCLUSIONS**

This study examined intra-population variation in body proportions among rural Amazonian adults in relation to a number of biocultural variables. The results indicated that:

1. Stunting in this population is accompanied by significant changes in body proportions only among female individuals, while no differences were detected among males.

Drawing on biocultural data, this pattern is interpreted as being related to differential opportunities for catch-up growth for males and females and to the costs of female reproduction.

2. Males and females in this population exhibited significantly different body proportions. Specifically, females expressed overall more compromised growth outcomes. This result contrasts with the hypothesis of greater male susceptibility. Thanks to rich biocultural data on this population this unexpected finding was explained as due to greater stressors experienced by females in association with reproduction. Therefore, this analysis does not provide support or refutation for the hypothesis of great male susceptibility.
3. Among all reproductive history parameters, age-at-first-birth was significantly correlated with terminal height and leg length. This result suggests that early reproduction may induce the cessation of growth in female adolescents, at least in underprivileged settings. While early pregnancy has generally been associated with poor birth outcomes, this is the

first study that provides evidence for negative maternal growth outcomes in relation to early reproduction.

Future research focused on early pregnancy and maternal growth may enlighten the relationship between somatic growth and specific environmental conditions and therefore provide insights for health and nutrition policy for underprivileged groups and adolescents mothers.

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## FIGURES AND TABLES

TABLE 1. Descriptive statistics for anthropometric data and age by subsample.

		<b>Height</b>	<b>Sitting Height</b>	<b>Total Leg Length</b>	<b>Age</b>
Males	N	84	84	84	84
	Min	136.9	72.5	64.4	18
	Max	179.4	91.0	94.7	77
	Mean	160.4	83.2	77.2	36.0
	St Dev	7.1	4.0	4.8	14.2
Females	N	88	88	88	88
	Min	122.0	70.9	43.8	18
	Max	160.2	87.2	78.8	66
	Mean	146.5	78.0	68.5	32.9
	St Dev	5.5	3.0	4.6	12.8

Male Stunted	N	32	32	32	32
	Min	136.9	72.5	64.4	18
	Max	159.8	90.8	82.9	77
	Mean	153.6	80.1	73.4	40.1
	St Dev	5.3	4.1	3.8	15.6
Male Non Stunted	N	52	52	52	52
	Min	159.0	80.2	73.7	18
	Max	179.4	91.0	94.7	66
	Mean	164.6	85.1	79.5	33.4
	St Dev	4.1	2.5	3.7	12.7
TABLE 1 cont'd		<b>Height</b>	<b>Sitting Height</b>	<b>Total Leg Length</b>	<b>Age</b>
Female Stunted	N	50	50	50	50
	Min	122.0	70.9	43.8	18
	Max	149.3	82.0	74.5	66
	Mean	143.1	76.9	66.3	34.4
	St Dev	4.6	2.9	4.5	12.4
Female Non Stunted	N	38	38	38	38
	Min	147.8	74.8	66.6	18
	Max	160.2	87.2	78.8	65
	Mean	150.9	79.5	71.4	30.8
	St Dev	3.0	2.4	2.7	13.1

TABLE 2. Reproductive characteristics of the women (n=88)

	Min	Max	Mean	St Dev
Menarche	11	16	12.8	1.1
Age at First Birth	13	24	17.8	2.3
Breastfeeding duration	4.3	25.6	13.4	4.3
Inter-birth Interval	10.75	73.0	27.5	10.7
Parity	1.0	15.0	6.2	4.0
Parity (women > 45 yrs) (n= 15)	2.0	15.0	10.3	3.8

TABLE 3. Correlation analysis between anthropometric data and reproductive history parameters, controlled for age and age at first birth.



Control	Variable		Height	Sitting Height	Total Leg Length
<i>Age</i>	Menarche	Correlation	0.195	0.123	0.158
		Significance (2-tailed)	0.098	0.298	0.182
		Degrees of freedom	71	71	71
	Age at First Birth	Correlation	<b>0.2891</b>	-0.044	<b>0.4122</b>
		Significance (2-tailed)	0.018 <sup>1</sup>	0.723	0.001 <sup>2</sup>
		Degrees of freedom	65	65	65
	Parity	Correlation	-0.133	-0.021	-0.145
		Significance (2-tailed)	0.22	0.85	0.18
		Degrees of freedom	85	85	85
<i>Age at first child</i>	Inter-birth Interval	Correlation	-0.135	-0.134	-0.072
		Significance (2-tailed)	0.389	0.392	0.645
		Degrees of freedom	41	41	41

<sup>1</sup> Significant at 0.05 level.

<sup>2</sup> Significant at 0.001 level.

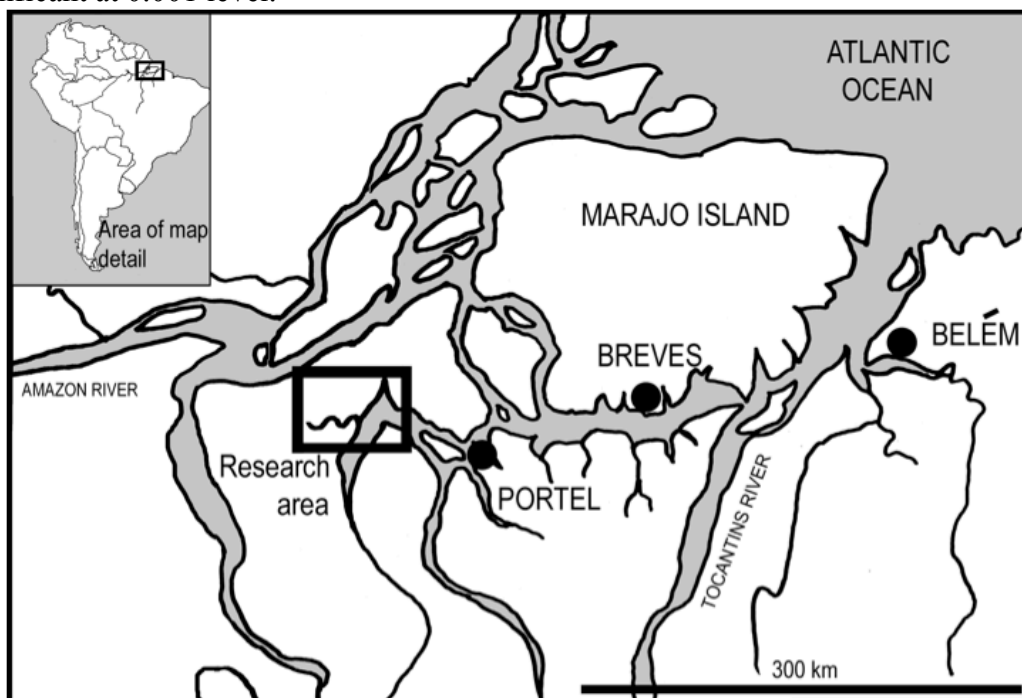


Figure 1. Map of the field site, from Piperata, 2007.

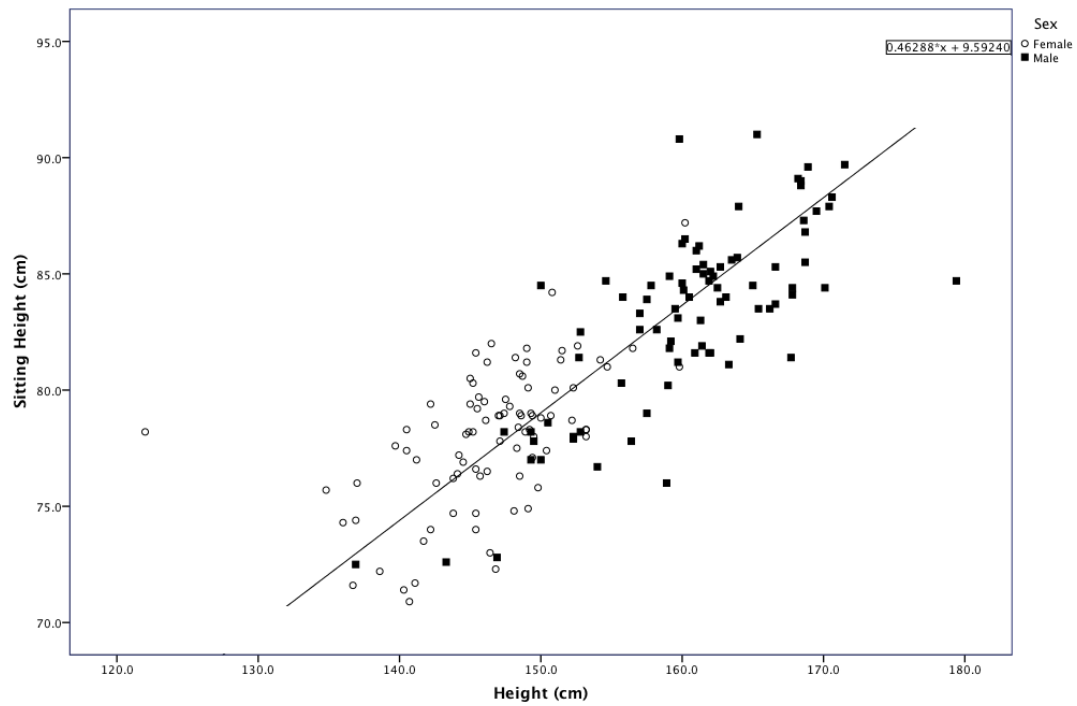


Figure 2. Scatter plot of Sitting Height over Height for males and females.

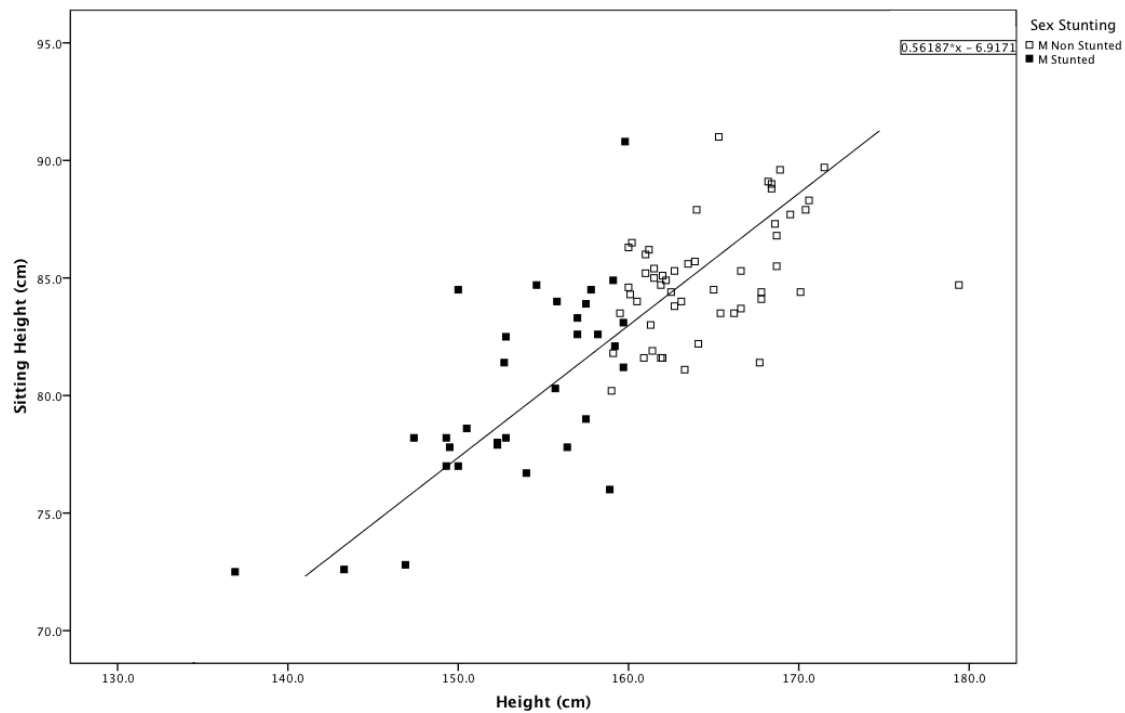


Figure 3. Scatter plot of Sitting Height over Height for stunted and non-stunted males.

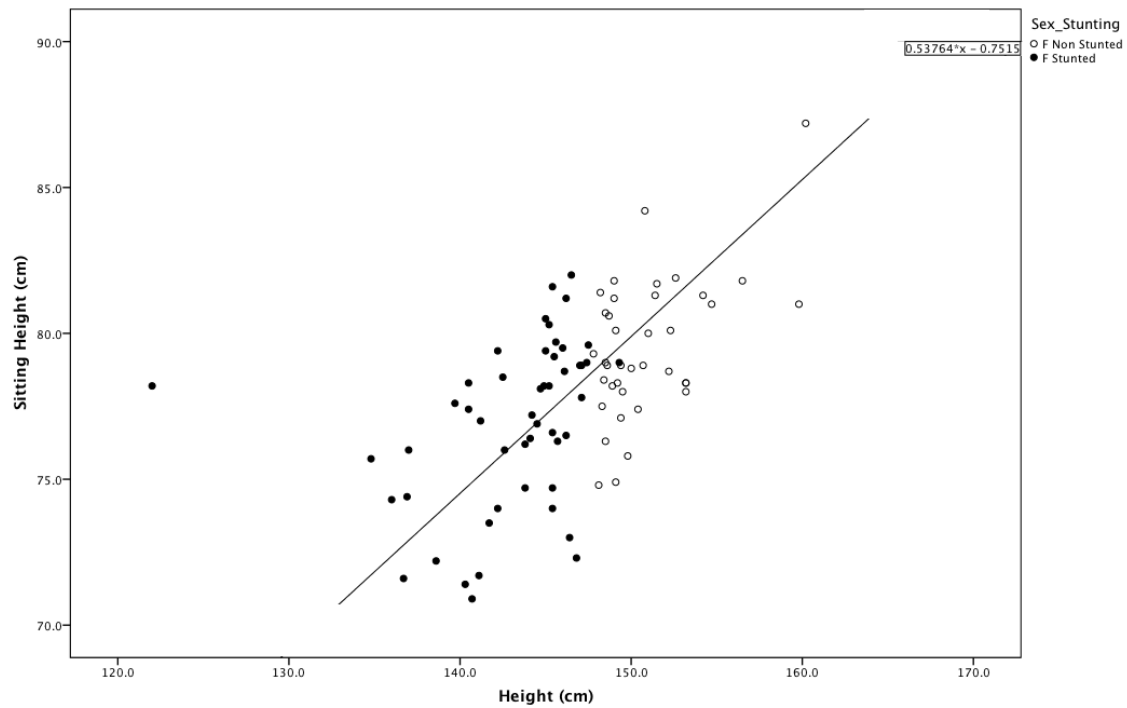


Figure 4. Scatter plot of Sitting Height over Height for stunted and non-stunted females.

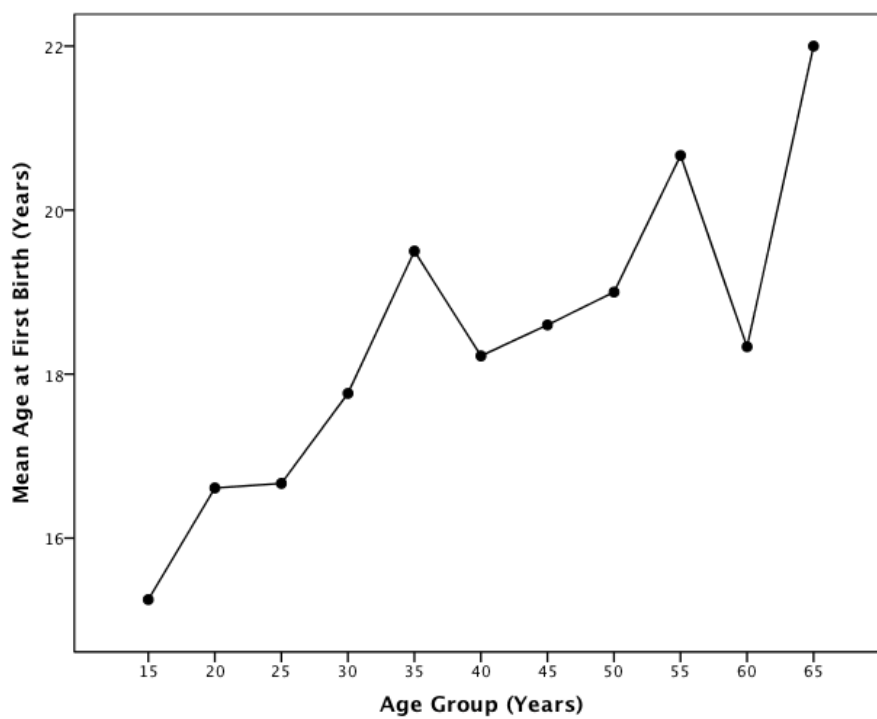


Figure 5. Secular trend in mean age-at-first-birth among *Riberinhos*.